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UNDER CONTRACT N00024-70-C-1184
6 April – 5 July 1972

NAVAL SHIP SYSTEMS COMMAND
Contract N00024-70-C-1184
Proj. Ser. No. SF 11121103, Task 8614

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ABSTRACT

The covariance functions of the fluctuating component of the narrowband reverberation envelope have been experimentally estimated and compared to the theoretical expressions appropriate to the transmitted signals. Two types of transmitted signals, cw and FM, were used to generate the reverberation processes. The scattering mechanisms were, as in previous experiments, the rough, moving surfaces of an inland lake. The results presented indicate that the normalized covariance of the envelope function of the reverberation can be reasonably predicted given the waveform of the transmitted signal that generated the reverberation process.

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I. INTRODUCTION

The research under this contract is centered on studying the statistical properties of the envelope of a narrowband reverberation process. We assume that the reverberation can be expressed as

$$X(t) = E(t) \cos[2\pi f_o t + \varphi(t)] \quad , \tag{1}$$

where f_o, $\varphi(t)$, and $E(t)$ are, respectively, the center frequency, the phase, and envelope of $X(t)$. We are primarily interested in the properties of the envelope $E(t)$ since it plays a key roll in many sonar systems. In particular the fluctuating component

$$y(t) \equiv E(t) - \langle E(t) \rangle \tag{2}$$

is the process being studied here. Given the waveform of the transmitted signal that produces $X(t)$, we seek to accurately predict the first- and second-order statistics of the stochastic process $y(t)$. Our starting point in this endeavor is the theoretical expression for the covariance of $y(t)$ obtained previously,[1,2]

$$\begin{aligned} K_y(t_1,t_2) &\equiv \langle y(t_1)y(t_2) \rangle \\ &= \frac{\pi}{8} \psi\, k_o^2(\tau) \quad , \quad \tau = t_2 - t_1 \quad , \end{aligned} \tag{3}$$

where ψ is the mean intensity of the narrowband reverberation $X(t)$ and $k_o(\tau)$ is the envelope of the normalized covariance of $X(t)$.

It is assumed that the covariance of X(t) is equivalent (within a scale factor) to the autocorrelation function $C(\tau)$ of the transmitted signal S(t). Thus we can write

$$k_o(\tau) = C_o(\tau) \quad , \tag{4}$$

where $C_o(\tau)$ is the envelope of $C(\tau)$. Specifying a particular waveform of the transmitted signal determines $C_o(\tau)$ and, hence, $k_o(\tau)$ (see the introduction of Ref. 1). Alternatively, these results can be expressed in the frequency domain. Thus the intensity spectrum of y(t) corresponds to a cw transmitted signal of duration T,

$$\left.\begin{aligned} W_y(f)_{cw} &= T\psi_{cw} \frac{\pi}{(\omega T)^2}\left[1 - \frac{\sin\omega T}{\omega T}\right] \quad , && \omega \geqq 0 \\ &= 0 \quad , && \text{elsewhere} \end{aligned}\right\} , \tag{5}$$

where ψ_{cw} is the intensity of X(t), the narrowband reverberation process. The corresponding expression for the reverberation produced by an FM signal of duration T and bandwidth W is

$$\left.\begin{aligned} W_y(f)_{FM} &= \frac{\pi\psi_{FM}}{4W}(1 - f/W) \quad , && 0 \leqq f \leqq W \\ &= 0 \quad , && \text{elsewhere} \end{aligned}\right\} . \tag{6}$$

In the previous period the validity of Eq. (5) was tested with an ensemble of data generated by scattering cw signals from the surface of Lake Travis. The results are summarized in Fig. 1. Also shown here is a comparison of theoretical and experimental estimates of the spectrums of the time average of y(t). The theoretical expression in this case is

$$W_Y(f) = \frac{1}{(\omega T)^2}\left(1 - \frac{\sin\omega T}{\omega T}\right)\frac{\sin^2(\omega T_o/2)}{(\omega T_o/2)^2} \quad , \quad \omega = 2\pi f \quad , \tag{7}$$

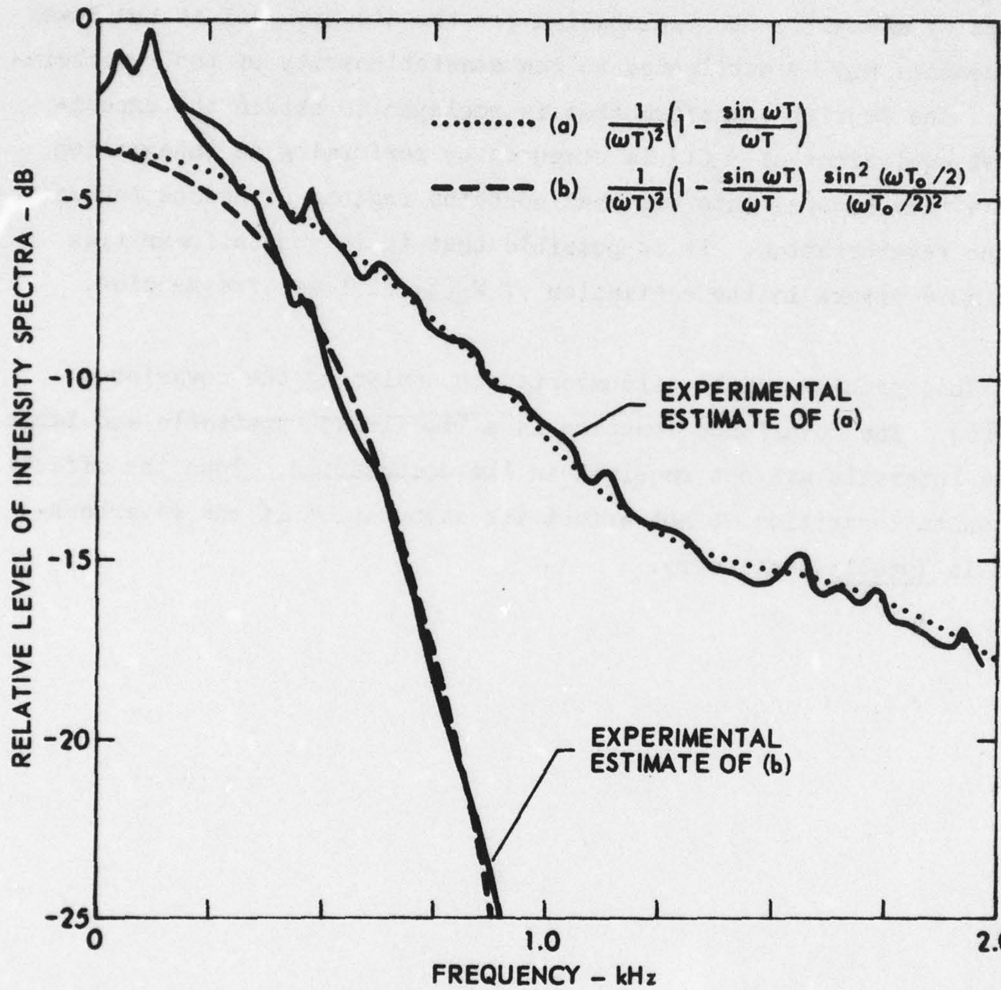

FIGURE 1
INTENSITY SPECTRA OF FLUCTUATING COMPONENT OF REVERBERATION ENVELOPE (a).
TIME AVERAGE ("SMOOTHED") OF FLUCTUATING COMPONENT OF REVERBERATION ENVELOPE (b).

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where T_o is the averaging time (see Sec. VII of Ref. 2). Good agreement between theory and experiment exists at all but the lower values of $\omega(=2\pi f)$. One explanation for the disagreement at the lower frequencies may be attributed to the nonstationarity of the reverberation. The Fourier transform that is employed to obtain the experimental equivalent of $W_Y(f)$ is computed by performing an integration over a time (range) interval that contains regions of nonstationarities of the reverberation. It is possible that these nonstationarities introduce errors in the estimation of $W_y(t)$ at lower frequencies.

This problem can be circumvented by analyzing the covariance of $y(t)$. The covariance function is a "localized" statistic and large range intervals are not required in its computation. Thus the effects of nonstationarities do not affect its computation if the reverberation is <u>locally</u> stationary.

II. EXPERIMENTAL DATA: ALTERNATING FM AND cw REVERBERATION

An important goal of this study is to compare some of the relative merits of transmitting FM and cw signals to detect an acoustic target whose echoes are reverberation limited. A partial understanding of this phase of the problem is achieved by investigating the statistical properties of the two reverberation processes generated by these signals, respectively. Thus the rough, moving surfaces of a fresh water lake were insonified by a series of alternating FM and cw signals of equal amplitude, pulse duration (4 msec), and center frequency (80 kHz). The bandwidth W of the FM signal was 2 kHz. By alternating the two signals, two processes (FM reverberation and cw reverberation) were generated almost simultaneously. Oscilloscope tracings of some of the reverberation returns can be seen in Fig. 2.

The data were originally recorded in analog form on magnetic tape and later converted to digital samples. The quadrature components were sampled directly at a rate of 16 kHz. Each digital record is 1600 samples long which corresponds to a time extent of 100 msec. The following table summarizes the digital data on tape 698.

DIGITAL TAPE 698

Sequence Number	Quadrature Component	Reverberation Return Number	Transmitted Signal
1	X	1	cw
2	Y		
3	X	2	FM
4	Y		
.	.	.	.
.	.	.	.
.	.	.	.
315	X	198	FM
316	Y		
317	X	199	cw
318	Y		

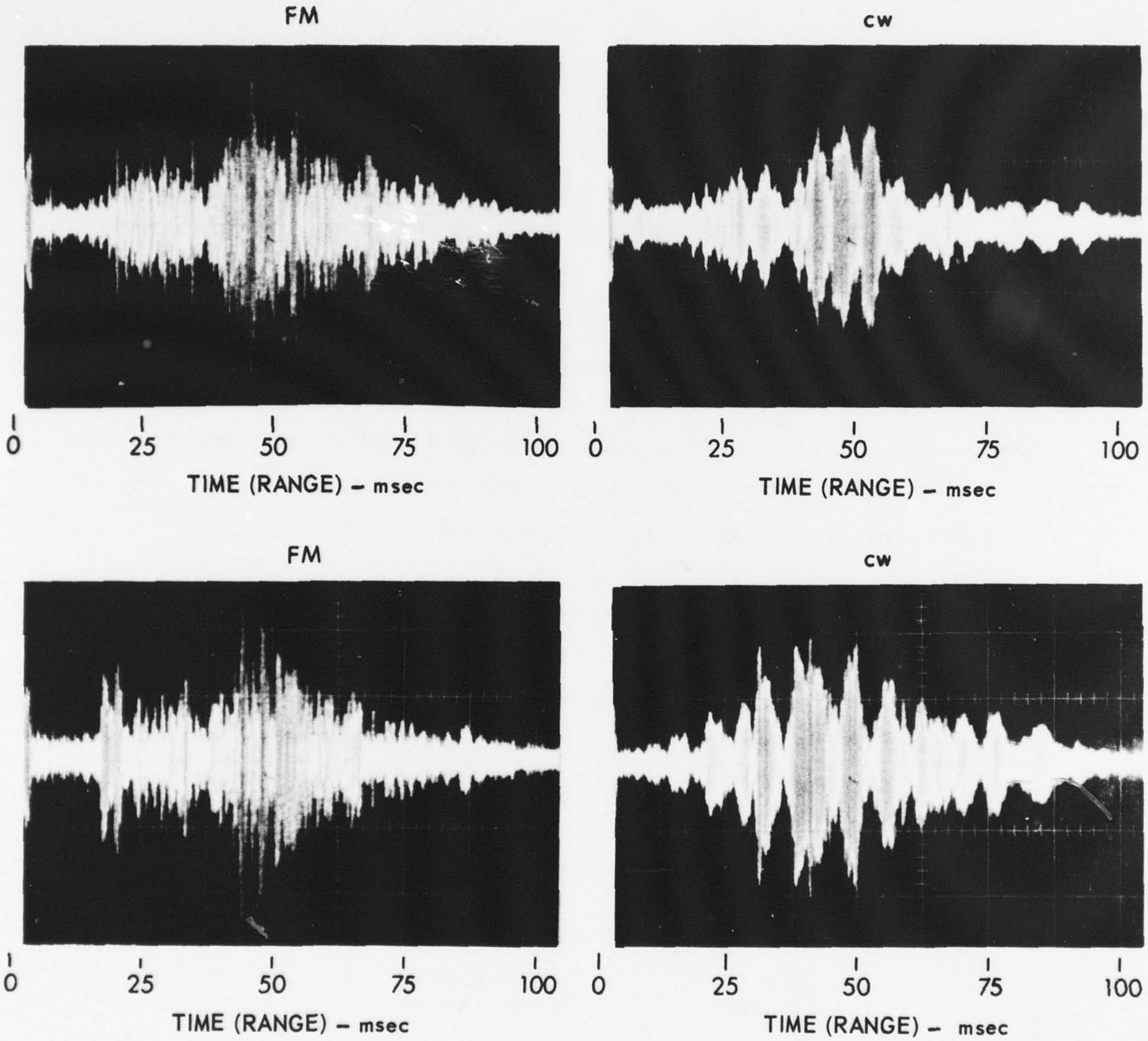

FIGURE 2
REVERBERATION RETURNS FROM THE ROUGH SURFACE OF A LAKE INSONIFIED BY FM (T = 4 msec, W = 2 kHz) AND cw (T = 4 msec) TRANSMITTED SIGNALS

The envelope is obtained by computing $\left[X^2+Y^2\right]^{1/2}$. The first six envelope functions of the records on tape 618 are plotted in Fig. 3. As expected the variations with respect to range of the FM reverberation are more rapid than the variations of the cw reverberations.

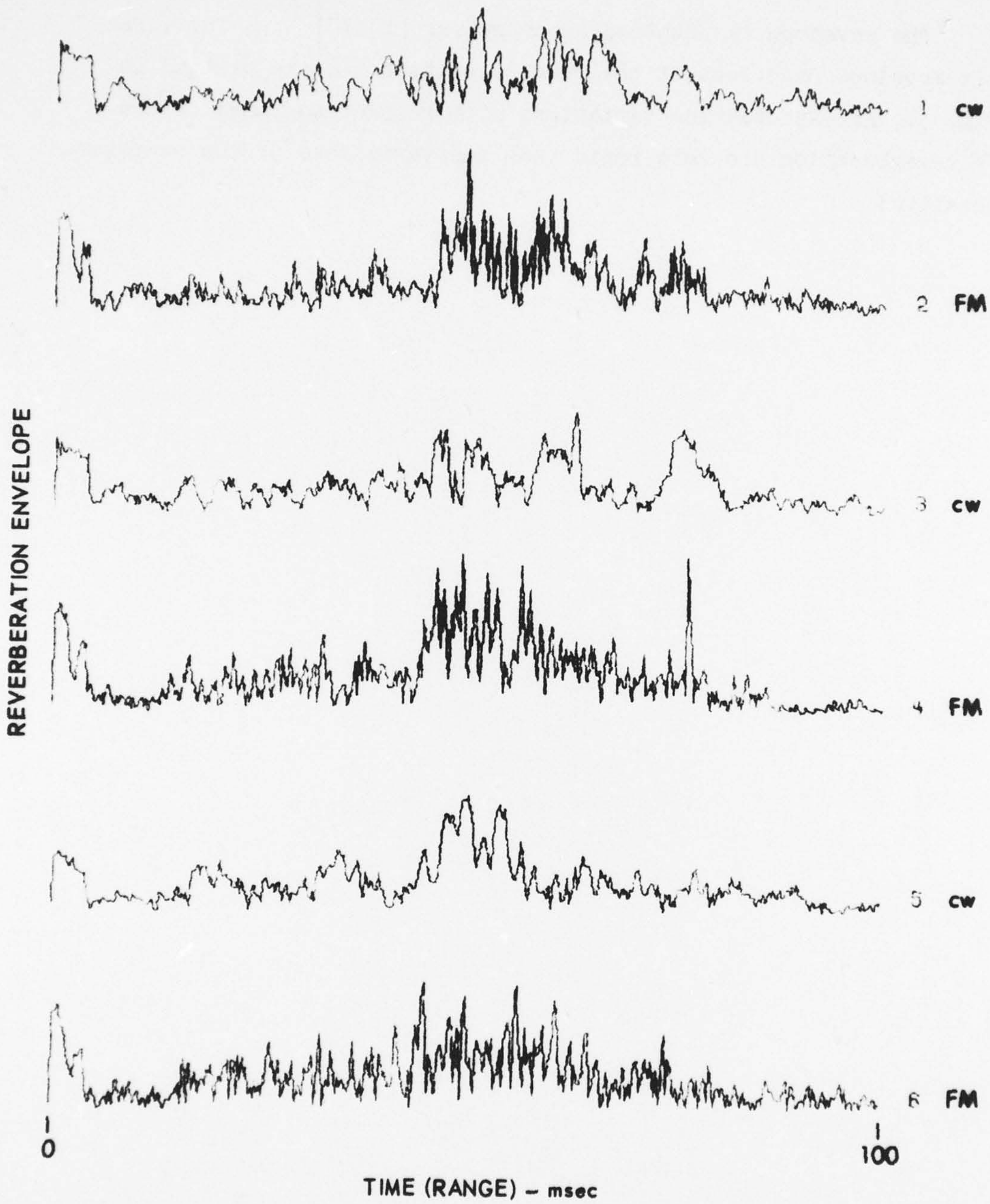

FIGURE 3
SIX CONSECUTIVE REVERBERATION RETURNS GENERATED
BY ALTERNATING cw AND FM TRANSMITTED SIGNALS

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III. INTENSITIES OF THE FM AND cw REVERBERATION

The theoretical intensity of y(t), the fluctuating component of the envelope E(t), is (see Sec. III of Ref. 1)

$$\left\langle y(t)^2 \right\rangle = \left(2 - \frac{\pi}{2}\right) \psi \cong 0.43\psi \quad , \tag{8}$$

where

$$\psi = \left\langle X(t)^2 \right\rangle \tag{9}$$

is the intensity of the narrowband reverberation X(t). Combining Eqs. (8) and (9) gives

$$\left\langle y(t)^2 \right\rangle \Big/ \left\langle X(t)^2 \right\rangle = 0.43 \quad , \tag{10}$$

which states that the ratio of these two quantities is independent of range.

In Fig. 4 the intensities of the cw and FM reverberation are plotted as functions of range. Since the FM and cw signals were of equal amplitude and pulse durations, their transmitted energies were equivalent and it is expected that the two corresponding reverberation intensities would be equal. In Fig. 4 one can see that the two intensities are approximately the same over all ranges. A similar conclusion made about the intensities of the fluctuating components is supported by the data plotted in Fig. 5.

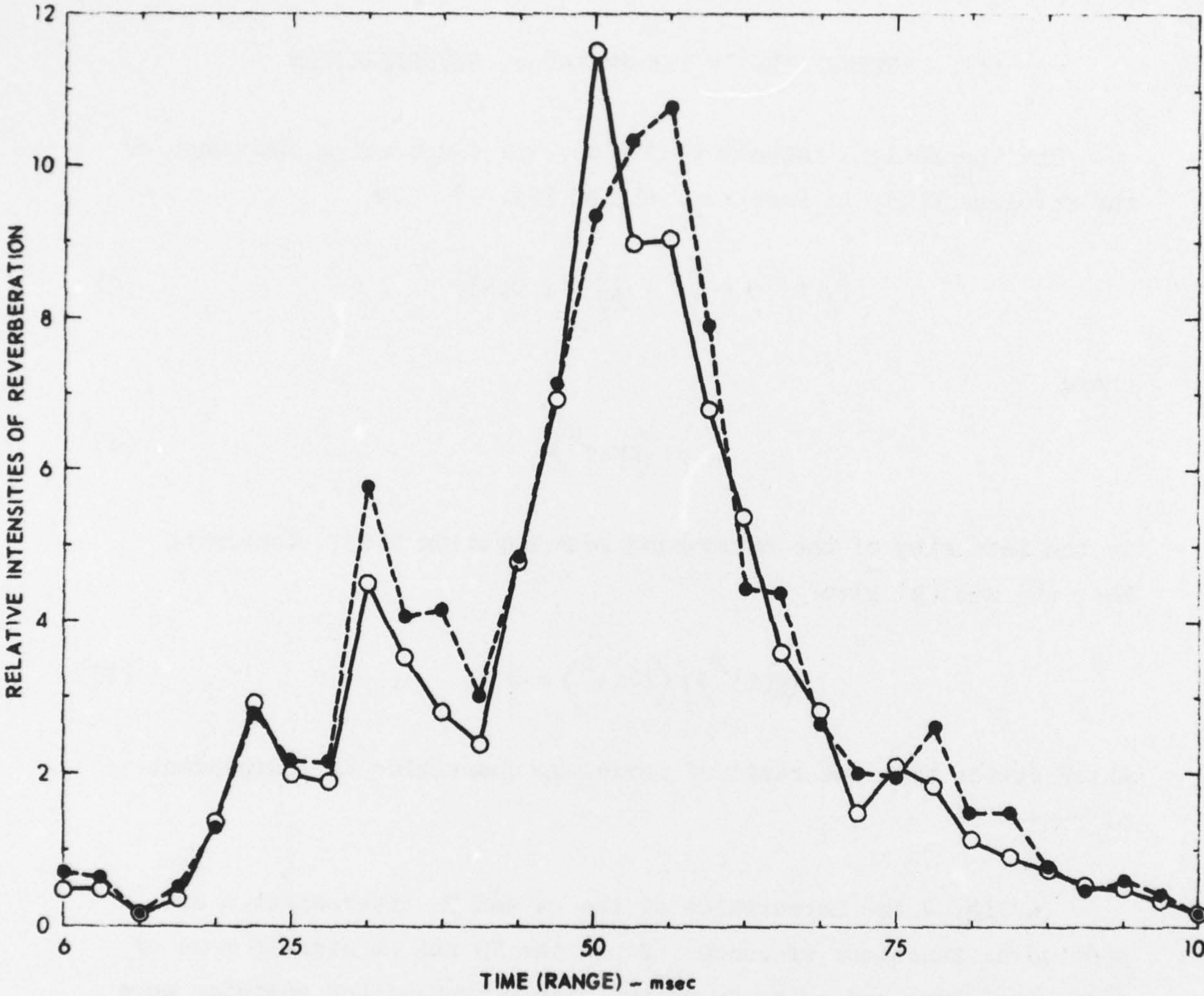

FIGURE 4
RELATIVE INTENSITIES OF REVERBERATION PROCESSES GENERATED BY INSONIFYING THE ROUGH, MOVING SURFACE OF A LAKE WITH FM AND cw SIGNALS

FM   cw

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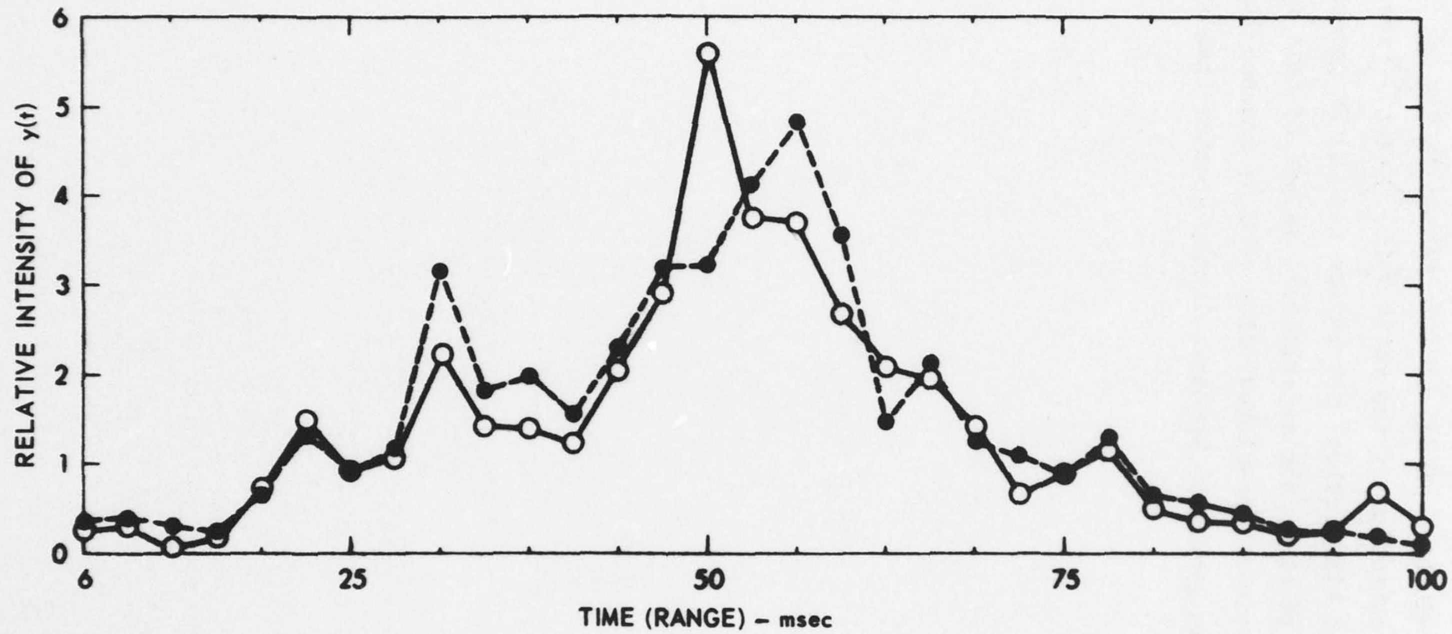

FIGURE 5
RELATIVE INTENSITIES OF THE FLUCTUATING COMPONENT, $y(t)$, OF REVERBERATION PROCESSES GENERATED BY INSONIFYING THE ROUGH MOVING SURFACE OF A LAKE WITH FM AND cw SIGNALS

●– – –● FM   ○——○ cw

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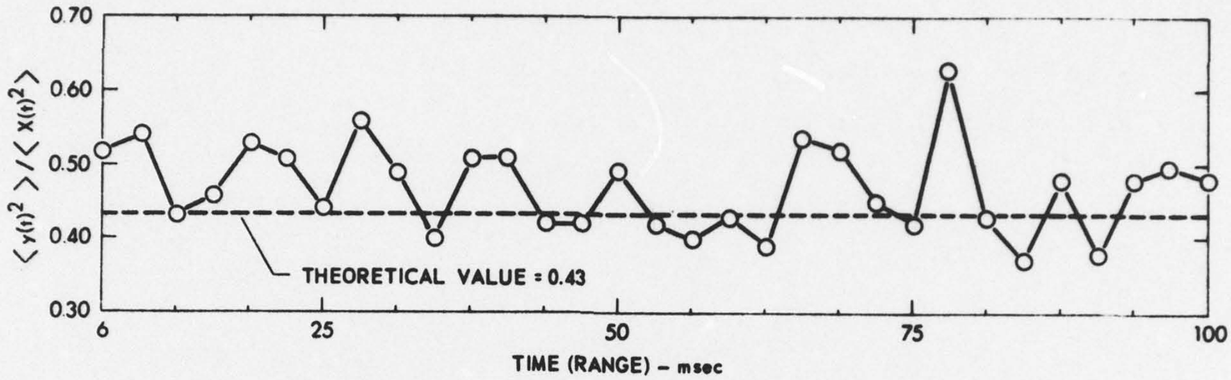
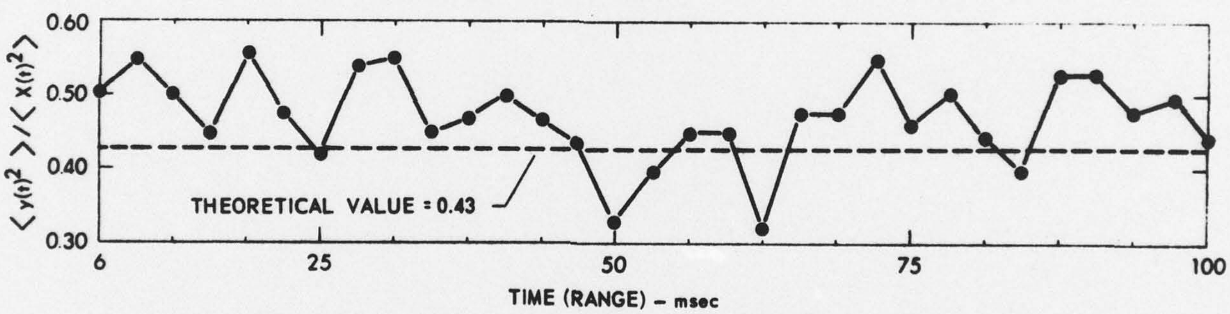
The theoretical prediction of Eq. (10) is tested in Fig. 6 where the experimental estimates of the ratio $\langle y(t)^2 \rangle / \langle x(t)^2 \rangle$ are plotted as a function of time (range) for (a) cw and (b) FM generated reverberation. As can be seen, the experimental values of this ratio are close to the theoretically predicted value of 0.43 (dashed line). However, these ratios do generally appear slightly greater than the expected value of 0.43.



cw TRANSMITTED SIGNAL



FM TRANSMITTED SIGNAL

FIGURE 6
BEHAVIOR OF $\langle y(t)^2 \rangle / \langle X(t)^2 \rangle$ AS A FUNCTION OF RANGE, WHERE $y(t)$ = FLUCTUATING COMPONENT OF ENVELOPE OF NARROW BAND REVERBERATION $X(t)$ GENERATED BY cw AND FM TRANSMITTED SIGNALS

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IV. EXPERIMENTAL COVARIANCE FUNCTIONS

The theoretical covariance of the fluctuating component y(t) is

$$K_y(\tau) = k_o(\tau)^2 \quad , \tag{11}$$

where $k_o(\tau)$ is the normalized envelope of the covariance of the narrowband reverberation process X(t). Figure 7 compares this theoretically predicted covariance to the experimental ensemble covariance (cw reverberation). For a cw transmitted signal of duration T we have (see Sec. VI of Ref. 2)

$$k_o(\tau) = 1 - \frac{\tau}{T} \tag{12}$$

and

$$K_y(\tau) = \left(1 - \frac{\tau}{T}\right)^2 \quad . \tag{13}$$

Each of these is drawn in Fig. 7 for comparisons with the corresponding experimental covariances. These covariances were estimated at the time t=75 msec following transmission.

Figure 8 shows the covariance structures of the FM reverberation. To obtain the theoretical prediction of $K_y(\tau)$ the square of the experimental narrowband reverberation was computed. The reason for this approach is that the bandwidth of the FM signal was not measured with sufficient accuracy to obtain a reasonable prediction of $K_y(\tau)$ or of $K_Y(\tau)$.

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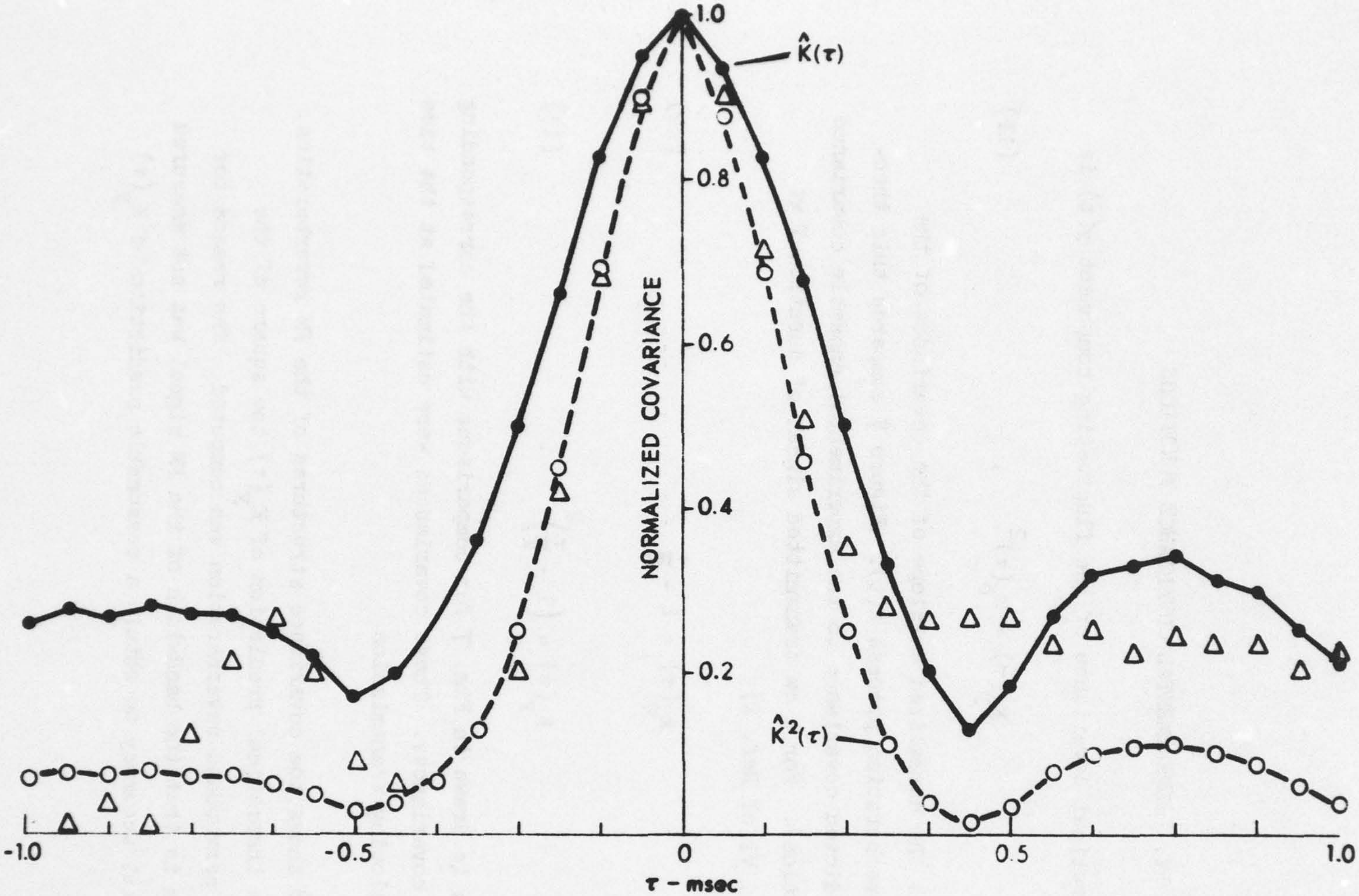

FIGURE 7
NORMALIZED COVARIANCE FUNCTIONS OF A NARROW BAND REVERBERATION PROCESS (FM TRANSMITTED SIGNAL) AND ITS ENVELOPE

$\hat{K}(\tau)$ – EXPERIMENTAL COVARIANCE OF NARROW BAND REVERBERATION

$\Delta\ \Delta$ – EXPERIMENTAL COVARIANCE OF REVERBERATION ENVELOPE

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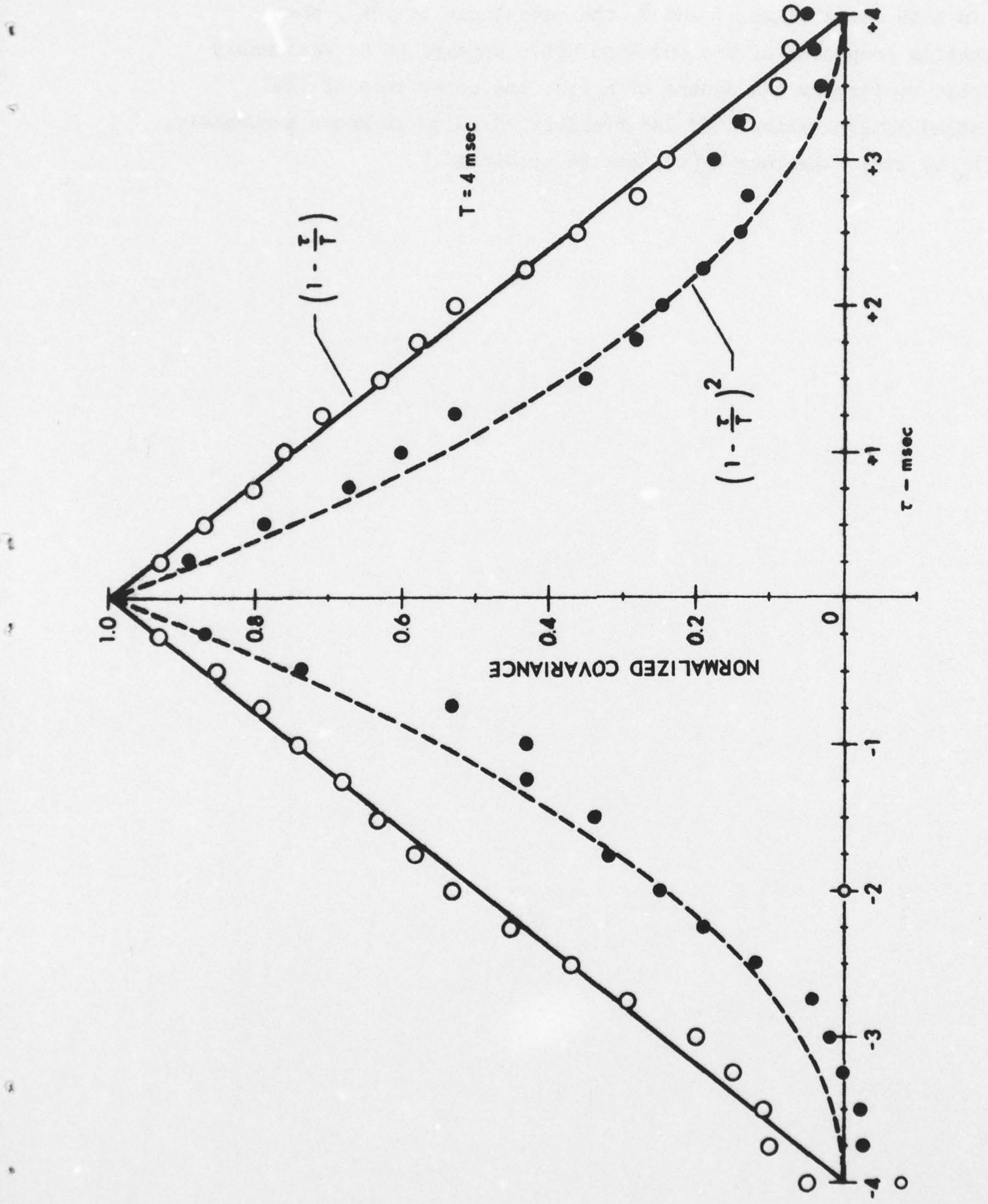

FIGURE 8
NORMALIZED COVARIANCE FUNCTIONS OF A NARROW BAND REVERBERATION PROCESS (cw TRANSMITTED SIGNAL)

○ – EXPERIMENTAL COVARIANCE OF NARROW BAND REVERBERATION
● – EXPERIMENTAL COVARIANCE OF REVERBERATION ENVELOPE

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In both cases (Figs. 7 and 8) the covariance of $y(t)$, the fluctuating component of the envelope $E(t)$, appears to be reasonably predicted by forming the square of $k_o(\tau)$, the covariance of the narrowband reverberation. If the transmitted pulse is known accurately, then $k_o(\tau)$ and, therefore $K_y(\tau)$, can be predicted.

V. CONCLUDING REMARKS

The results presented in this progress report indicate that the normalized covariance of the envelope function of a narrowband reverberation process can be predicted from a knowledge of the transmitted waveform. Thus, if the autocorrelation function of the narrowband reverberation is of the form

$$K(\tau) = k_o(\tau) \cos(2\pi f_o \tau) \quad ,$$

where f_o is the center frequency of the transmitted signal, then the covariance function, $K_y(\tau)$, of the envelope of the reverberation is approximately $k_o^2(\tau)$.

A knowledge of $K_y(\tau)$ is useful in analyzing the performances of sonar receivers that extract, in some manner, their information from the envelope of the received signal (reverberation-plus-target echo). Accordingly the next and final phase of this research project will be applied to studying the properties of the reverberation envelope after it has been subjected to a time average ("smoothing"). As part of this study artifical target echoes will be added to the reverberation in both the FM and cw cases. Thus, an accurate comparison of transmitting FM and cw signals can be made in the case of a detector-averager type of receiver.

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1. Quarterly Progress Report No. 7 under Contract N00024-70-C-1184, 5 July - 5 October 1971, Applied Research Laboratories, The University of Texas at Austin (16 November 1971).

2. Quarterly Progress Report No. 8 under Contract N00024-70-C-1184, 5 October 1971 - 5 January 1972, Applied Research Laboratories, The University of Texas at Austin (7 January 1972).

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